### NOISE PROPERTIES OF A TRANSVERSE DAMPER FOR THE LHC

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### **Introduction**

This paper will use the analysis developed in the paper "A Transverse Damper System for the SPS in the Era of the LHC" to analyze the noise properties of a transverse damper for the LHC. Table 1 is a list of some of the relevant parameters for the damper system. Figure 1 is the configuration of the damper system. Table 2 is the results of the analysis. Figure 2 is the normalized emittance growth rate versus damping time. The reason for the change in slope of curve at short damping times is due to signal suppression. Figure 3 is the noise power at the kicker as a function of damping time.

The emittance growth rates in Figure 2 are rather large. The only way to reduce these rates is to increase the gain on the front end of the damper (i.e. make a more sensitive pickup). However, there are two separate reasons which make increasing the front end gain difficult. The first reason is due to the size of the closed orbit variations through the pickup as the accelerator is ramped. Because any closed orbit suppression technique will produce some noise into the system, the larger the closed orbit variation, the larger the amount of noise that is produced.

Secondly, the damper system has active electrical components that process the pickup signal (i.e. the digitzer, amplifiers, etc.) Because these components have a limited dynamic range, they must be protected from large voltages that might be produced during an injection transient. Since injection transients exist only for a short period of time, the gain distribution of the damper could be re-arranged after the transients are gone. However, rearranging the gain blocks of the damper system might require active switches and/or attenuators which themselves might have a limited dynamic range.

Table 1. Damper System Specifications

Bamper System Specifications	
	25 nS
	1.6x10 <sup>11</sup>
	3 nS
	11 kHz
Injection	450 GeV
Extraction	7500 GeV
	68.3
	0.1%
	40 mm
	15% full aperture
e pickup	1 mm
	170 m
	40 mm
	0.66
	0.9375 m
	50 Ω
	100 m
	40 mm
	Injection Extraction

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Kicker sensitivity (g <sub>k</sub> )	0.66
Kicker length (l <sub>k</sub> )	1.500 m
Kicker Impedance (Z <sub>O</sub> )	$50 \Omega$
Kicker Voltage (V <sub>k</sub> )	2000 V
Front End Bandwidth (Wf)	80 MHz
Kicker Bandwidth	>20 MHz
Conversion gain of pulse shaping mixer (g <sub>m</sub> )	-6 dB
Digitizer resolution	10 bits
Maximum voltage before the A/D is destroyed(VA/Dmax)	2 V
Maximum output voltage of the closed orbit suppression multiplier(VAD834max	) 0.3 V
Noise Spectral density of the closed orbit suppression multiplier(S <sub>AD834</sub> )	-147 dBm/Hz
Gain of amplifier down stream of multiplier (Gmco)	20 dB

Table 1. (continued)

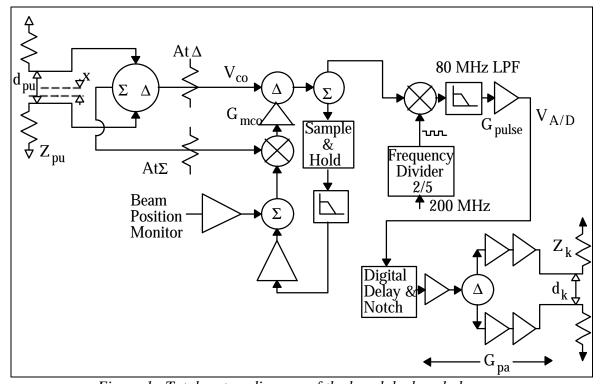


Figure 1. Total system diagram of the bunch by bunch damper.

Decoherence time	318 turns
Saturated Damping time	54 turns
Front End attenuator $(1/gAt\Delta)$	24 dB
Front End amplifier gain (g <sub>pulse</sub> )	36 dB
Total Electronic gain (geNturns/E)	106 dB-turns/TeV

Table 2. Results of damper analysis

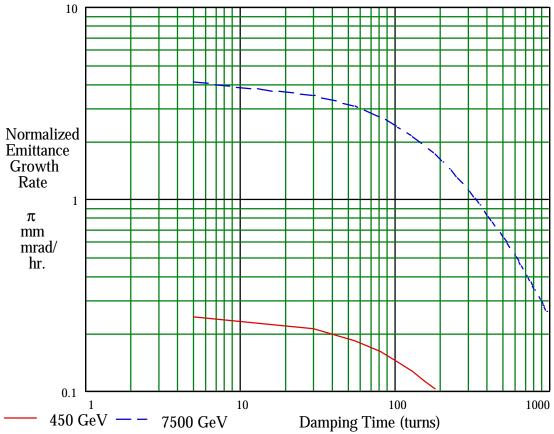
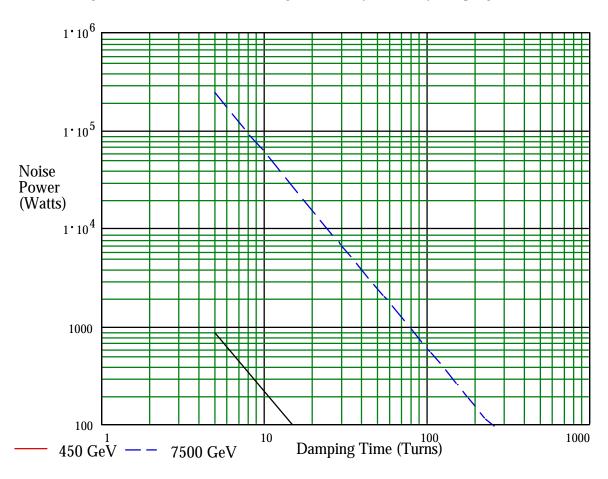
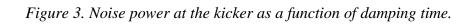


Figure 2. Normalized emittance growth as a function of damping time.





# Summary of Equations

Beam current response after it has been filtered:

$$i_b(t)*f(t) = \frac{qN_b}{\sqrt{2\pi(\sigma_b^2 + \sigma_f^2)}} e^{-\frac{1}{2}\frac{t^2}{(\sigma_b^2 + \sigma_f^2)}}$$
 (A1)

$$\sigma_{\rm f} = \frac{1}{2\pi W_{\rm f}} \tag{A2}$$

To hold true, the falloff of the filter should be at least 12 dB/octave.

The kicker deflection angle:

$$\theta_{k} = 2g_{k} \frac{L_{k}}{d_{k}} \frac{q}{pc} = \frac{d\theta_{k}}{dV_{k}} V_{k}$$
(A3)

Betatron amplitude as a function of time for a linear damper:

$$\frac{x_{pu}(t)}{\sqrt{\beta_{pu}}} = a(t) = a_0 e^{-\frac{t}{N_{turns}T_r}}$$
(A4)

$$\frac{1}{g_e N_{turns}} = \frac{1}{\sqrt{2}} g_{pu} \frac{Z_o}{2} \left( \left( i_b \left( t + \frac{L_{pu}}{c} \right) + i_b \left( t - \frac{L_{pu}}{c} \right) \right) * f(t) \right)_{t=0} \frac{d\theta_k}{dV_k} \frac{\sqrt{\beta_{pu}\beta_k}}{dp_u}$$
(A5)

Betatron amplitude as a function of time for a saturated damper:

$$a(t) = \frac{x_{\text{inj}}}{\sqrt{\beta_{\text{ini}}}} \left( 1 - \frac{t}{N_{\text{sat}} T_{\text{r}}} \right)$$
 (A6)

The damping time is:

$$N_{\text{sat.}} = \frac{\pi}{2} \frac{x_{\text{inj}}}{\sqrt{\beta_{\text{inj}} \beta_k}} \frac{1}{\frac{d\theta_k}{dV_k} V_{\text{k max}}}$$
(A7)

Decoherence 1/e time:

$$T_{decoh} = \frac{T_{rev}}{\pi \Lambda \Omega} = N_{dc} T_{rev}$$
 (A8)

Phase advance between pickup to kicker needed for a damper with an  $\mathbf{x}$  turn delay and a  $\mathbf{y}$  turn notch:

$$\phi_{pk} = \pi(m - Q(2x - y)) \tag{A9}$$

where m= any integer.

Coupled bunch mode **m** damping time:

$$\frac{1}{\tau_{\rm m}} = \frac{\sin(\pi Qy)}{N_{\rm turns}T_{\rm r}} K_{\rm pa}(m) \tag{A10}$$

$$K_{pa}(m) = h\omega_{r} \frac{\operatorname{Re}\left(\sum_{l=-\infty}^{\infty} R_{k}(\omega_{mq_{l}}) R_{pa}(\omega_{mq_{l}}) V_{D}(\omega_{mq_{l}})\right)}{\int_{-\infty}^{\infty} V_{D}(\omega) d\omega}$$
(A11)

$$\omega_{mq_1} = (lh + m + Q)\omega_r \tag{A12}$$

where the bunch spacing is  $T_r/h$ .

Normalized stripline kicker responsewith zero group delay:

$$R_{k}(\omega) = \frac{\sin\left(\omega \frac{L_{k}}{c}\right)}{\omega \frac{L_{k}}{c}}$$
(A13)

Normalized Butterworth 12dB/octave filter with zero group delay:

$$R_{pa}(\omega) = \frac{e^{j\sqrt{2}\frac{\omega}{2\pi f_{3dB}}}}{1 - \left(\frac{\omega}{2\pi f_{3dB}}\right)^2 + j\sqrt{2}\frac{\omega}{2\pi f_{3dB}}}$$
(A14)

Normalized frequency response of the D/A pulse with zero group delay:

$$V_{D}(\omega) = \frac{\sin\left(\pi \frac{\omega}{2\pi f_{clock}}\right)}{\pi \frac{\omega}{2\pi f_{clock}}}$$
(A15)

Normalized emittance growth rate due to noise power:

$$\frac{1}{\pi} \frac{d\varepsilon_{n}}{dt} = \gamma \beta f_{r}^{2} \beta_{k} \theta_{ns}^{2} \sum_{m=-\infty}^{\infty} \frac{dK_{\theta} ((m+Q)\omega_{r})}{df}$$
(A16)

$$\frac{dK_{\theta}(\omega)}{df} = \frac{\left|R_{k}(\omega)R_{pa}(\omega)V_{D}(\omega)\right|^{2}}{\int_{-\infty}^{\infty} \left|V_{D}(\omega)\right|^{2} df}$$
(A17)

$$\theta_{ns} = \frac{d\theta_k}{dV_k} \sqrt{Z_k \langle P_k \rangle} \tag{A18}$$

$$\langle P_k \rangle = \frac{\left(G_{pa}V_{bit}\right)^2}{Z_0} + \left(g_e \sin(\pi Qy)\right)^2 \langle P_{pu_{noise}} \rangle$$
 (A19)

Emittance growth due to uniform noise:

$$\frac{1}{\pi} \frac{d\varepsilon_{n}}{dt} = \gamma \beta f_{r} \beta_{k} \theta_{ns}^{2} K_{\theta}$$
 (A20)

including signal suppression:

$$\frac{1}{\pi} \frac{d\varepsilon_{n}}{dt} = \gamma \beta f_{r} \beta_{k} \left( \frac{\theta_{ns}}{1 + \frac{N_{dc}}{N_{turns}}} \right)^{2} K_{\theta}$$
(A21)

Gain of front end electronics (See Figure 14):

$$g_{At\Delta}g_{pulse} = \frac{\sqrt{2}V_{A/D_{max}}}{g_{pu}g_{m}\frac{Z_{o}}{2}\left(\left(i_{b}\left(t + \frac{L_{pu}}{c}\right) + i_{b}\left(t - \frac{L_{pu}}{c}\right)\right) *f(t)\right) \frac{x_{pu_{inj}}}{d_{pu}}}$$
(A22)

$$g_{At\Delta} = \frac{G_{mco} V_{AD834_{max}}}{\sqrt{2} g_{pu} \frac{Z_0}{2} i_b(0) \frac{x_{pu_{co}}}{d_{pu}}}$$
(A24)

$$G_{pa} = \frac{2g_e}{g_m g_{At\Delta}g_{pulse}}$$
 (A23)

Noise power at the kicker:

$$\left\langle P_{k} \right\rangle = \frac{\left(G_{pa}V_{bit}\right)^{2}}{Z_{o}} + \left(\frac{g_{e}G_{mco}}{g_{At\Delta}}\sin(\pi Qy)\right)^{2} S_{AD834}W_{f} \tag{A25}$$



## Appendix B

# **Symbols**

N<sub>b</sub> number of particles in a bunch

q electric charge

4σb bunch length at the base
 Wf 3dB band width of the filter
 gk sensitivity of the kicker,

 $\begin{array}{ccc} V_k & & \text{kicker voltage} \\ L_k & & \text{length of the kicker} \\ d_k & & \text{aperture of the kicker} \\ p & & \text{beam momentum.} \\ T_r & & \text{revolution period} \end{array}$ 

gpu sensitivity of the pickup Z<sub>O</sub> impedance of the pickup

d<sub>pu</sub> pickup aperture Lpu pickup length

ge total damper electronic gain

 $\begin{array}{ll} \beta_{pu} & \text{pickup beta function} \\ \beta_{k} & \text{kicker beta function} \end{array}$ 

Q betatron tune

φ<sub>pk</sub> phase advance between pickup to kicker

 $\omega_{r}$  revolution frequency in radian/sec

c velocity of light

f<sub>clock</sub> frequency of digitizer clock in Hz f<sub>3dB</sub> 3 dB cutoff frequency of amplifier γ ratio of particle mass to rest mass

 $\beta$  ratio of particle velocity to the velocity of light  $G_{pa}$  maximum gain of the power amplifier chain

Vbit resolution of the digitizer

<Ppunoise> Equivalent noise power of the damper front end referenced to the

output of the pickup hybrid

Z<sub>k</sub> impedance of the kicker

gm Conversion gain of pulse shaping mixer

VA/D<sub>max</sub> Maximum voltage before the A/D is destroyed

VAD834<sub>max</sub> Maximum output voltage of the closed orbit suppression multiplier
SAD834 Noise power spectral density of the closed orbit suppression multiplier